Article

Research on Hydrogen Production System Technology Based on Photovoltaic-Photothermal Coupling Electrolyzer

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Abstract: Solar hydrogen production technology is a key technology for building a clean, low-carbon, safe, and efficient energy system. At present, the intermittency and volatility of renewable energy have caused a lot of "wind and light." By combining renewable energy with electrolytic water technology to produce high-purity hydrogen and oxygen, which can be converted into electricity, the utilization rate of renewable energy can be effectively improved, while helping to improve the solar hydrogen production system. This paper summarizes and analyzes the research status and development direction of solar hydrogen production technology from three aspects. Energy supply mode: the role of solar PV systems and PT systems in this technology is analyzed. System control: the key technology and system structure of different types of electrolytic cells are introduced in detail. System economy: the economy and improvement measures of electrolytic cells are analyzed from the perspectives of cost, consumption, efficiency, and durability. Finally, the development prospects of solar hydrogen production systems in China are summarized and anticipated. This article reviews the current research status of photovoltaic-photothermal coupled electrolysis cell systems, fills the current research gap, and provides theoretical reference for the further development of solar hydrogen production systems.

Keywords: solar energy; hydrogen production; coupling; economic analysis

1. Introduction

Starting from 2021, China will implement policies related to "carbon peak" and "carbon neutrality" by building an environmentally friendly, green, energy-saving, and consumption-reducing energy system, thereby increasing the proportion of renewable energy. Faced with the increasingly severe challenge of the climate crisis, China has announced the “3060” dual-carbon target[1]. Renewable energy has the characteristics of clean and recyclable utilization, with great development prospects. In renewable energy, solar energy is easy to obtain and can be used for power generation, heating, refrigeration, hydrogen production, and seawater desalination, with broad application prospects[2]. The development and utilization of solar energy have been jointly addressed by experts in relevant fields both domestically and internationally. However, due to factors such as climate change, location, and changes in day and night, there are intermittent and fluctuating barriers to solar energy utilization, which are the main technical difficulties in the process of utilizing renewable energy for power generation. Using solar energy to produce hydrogen is a highly promising method [3]. On the one hand, it alleviates the intermittent and unstable usage defects of solar energy, converting it into high-calorific-value...
Hydrogen energy that can be stored, transported, and burned. On the other hand, it also provides research directions for the further development of solar energy conversion technology in the future.

Hydrogen energy is widely regarded as one of the most promising renewable energy sources due to its advantages, such as cleanliness and zero carbon [4]. To address climate change and ensure energy security, countries around the world have made the development of hydrogen energy an important strategic choice. In this context, major energy-consuming countries have listed research on solar hydrogen production technology as their national strategic plans. Table 1 lists the key contents and development goals of some national hydrogen energy strategic plans [5–7]. At present, various countries are vigorously promoting the development of hydrogen energy. More than 20 countries and regions, including China, the United States, Japan, and Australia, have formulated national hydrogen energy development strategies and actively cultivate technological research and industrial development in hydrogen energy and fuel cells. With the implementation of hydrogen energy strategies in various countries around the world, the integration of the hydrogen energy innovation chain and industrial chain is becoming increasingly close, and the application scenarios are gradually diversified. Among them, reliable, economical, and sustainable hydrogen production is the foundation of industrial development, and renewable energy hydrogen production has become the mainstream development direction. Under the current global energy structure, utilizing solar energy to achieve efficient hydrogen production is a very important measure [8–10]. Solar systems are divided into photovoltaic systems and photothermal systems. Photovoltaic-photothermal coupled electrolytic cells can utilize concentrated solar energy technology to provide heat to the electrolytic cells through thermal cycling, thereby powering the hydrogen production system [11]. Photovoltaic technology can be used to provide electricity for the hydrogen production system and generate heat for the electrolysis tank through an electric heater. Concentrated solar energy technology and photovoltaic technology can be used to provide the required thermal and electrical energy for the hydrogen production system, respectively [12–15]. The use of solar energy systems to supply power to hydrogen production units can not only suppress and absorb renewable energy, but also achieve the goal of peak shaving and “peak shifting and valley filling” in the power grid [16]. Therefore, solar photovoltaic-photothermal coupling hydrogen production is currently one of the most promising renewable energy hydrogen production methods.

### Table 1. Comparison of hydrogen energy strategy development among different countries.

<table>
<thead>
<tr>
<th>Country</th>
<th>Time</th>
<th>Development Goals</th>
<th>Key Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>2025</td>
<td>Preliminary establishment of hydrogen production and hydrogen production system. Since 2019, at least 18 provincial-level administrative regions in China have announced their goals for hydrogen energy development. By 2025, China will have at least 762 hydrogen refueling stations, 88,000 fuel cell vehicles, and a hydrogen energy industry scale of nearly 700 billion yuan.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2030</td>
<td>Forming a relatively complete hydrogen production and supply system.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2035</td>
<td>Forming a hydrogen-energy industry system.</td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>2030</td>
<td>The cost of hydrogen production has been reduced to 30 yen/Nm³; the hydrogen supply reaches 3 million tons per year. By 2030, the proportion of hydrogen/ammonia power generation will have achieved a breakthrough, increasing from 0%, as set in the fifth phase plan, to 1%, as set in this project.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>The cost of hydrogen production has been reduced to 20 yen/Nm³; the hydrogen supply reaches 20 million tons per year.</td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>2030</td>
<td>The cost of the electrolytic cell has been reduced to $300 per kilowatt, the operating life has reached 80,000 h, the system conversion efficiency has reached 65%, the hydrogen price Research, develop and validate technologies related to hydrogen conversion, and address institutional and market barriers, ultimately achieving widespread application across different fields.</td>
<td></td>
</tr>
</tbody>
</table>
for industrial and power sectors has been reduced to $1 per kilogram, and the hydrogen price for transportation sectors has been reduced to $2 per kilogram.

<table>
<thead>
<tr>
<th>European Union</th>
<th>2024</th>
<th>Install 6 million kW electrolysis facilities to produce 1 million tons of green hydrogen.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2030</td>
<td>Install 40 million kW electrolysis facilities to produce 10 million tons of green hydrogen.</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>All industrial sectors with high decarbonization difficulty coefficients will use green hydrogen as a substitute.</td>
</tr>
</tbody>
</table>

This provides direction for the development of the entire hydrogen production, storage, and transportation industry chain in Europe for the next 30 years and outlines a comprehensive investment plan. The total investment is expected to exceed 450 billion euros.

At present, there is relatively little comprehensive research on solar hydrogen production abroad, and the analysis of its energy supply system is not in-depth enough. Therefore, this article is dedicated to studying the coupling between solar energy supply systems and hydrogen production systems in electrolytic cells, and analyzing the respective roles of solar photovoltaic and photothermal systems in this system. This article provides a detailed introduction to the key technologies and system structures of different types of electrolytic cells and describes their characteristics using corresponding models and classic systems. In addition, the economy of the electrolytic cell and improvement measures were also analyzed. A statistical analysis was conducted on the current situation of hydrogen production systems in terms of cost, consumption, efficiency, and durability. The prospects for further development of hydrogen-related technologies were analyzed in detail. The main problems and bottlenecks of solar coupled hydrogen production systems were analyzed and proposed, and optimization ideas and plans were provided. In summary, this article summarizes and prospects the development prospects of solar hydrogen production systems, providing theoretical reference for further development of solar hydrogen production systems.

2. Current Status of Photovoltaic-Photothermal Development

Currently, researchers from various countries have conducted extensive research on solar hydrogen production technology. This section will start with the research background and current status of photovoltaic-photothermal technology, and discuss in detail the research status of photovoltaic-photothermal coupled electrolysis cell hydrogen production, providing reference for the large-scale application of solar hydrogen production technology.

2.1. Research Status

As early as the 19th century, scholars proposed the photovoltaic effect. With the continuous deepening of research, various research methods have emerged in the field of solar photovoltaic technology. Solar photovoltaic (PV) technology can utilize solar panels to absorb sunlight, thereby directly converting the radiant energy of sunlight into electrical energy. At this point, the form of current is direct current. To turn it into AC power, which is suitable for general use, you need to add equipment such as inverters. Solar photovoltaic technology is a clean energy technology [17] that produces low environmental pollution during use and has advantages such as renewability and sustainability. Therefore, it is highly praised. Solar photovoltaic technology is suitable for various applications, such as solar photovoltaic power plants, photovoltaic agriculture, and rooftop solar photovoltaic power generation. At present, solar photovoltaic technology is mainly applied in the field of power generation, including large-scale solar power plants and distributed photovoltaic power generation. At the same time, solar photovoltaic technology is gradually being promoted in fields such as construction and transportation. Table 2 summarizes the
different research methods of solar photovoltaic technology and the main research conclusions obtained under different technological applications.

**Table 2. Overview of solar photovoltaic system research.**

<table>
<thead>
<tr>
<th>Research Method</th>
<th>Serial Number</th>
<th>Technology Application</th>
<th>Main Content</th>
<th>Main Conclusions</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Power Point (MPPT)</td>
<td>1</td>
<td>Non-uniform illumination</td>
<td>Uneven illumination of photovoltaic arrays leads to a maximum power point shift, resulting in a decrease in output power.</td>
<td>The MPPT algorithm reduces tracking performance.</td>
<td>[18,19]</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Double fuzzy control</td>
<td>A maximum power point tracking method for photovoltaic cells combining dual fuzzy control and PID controller has been proposed.</td>
<td>Improvement of the efficiency and stability of solar energy conversion in photovoltaic cells.</td>
<td>[20]</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Variable step conductance increment method</td>
<td>A composite control strategy based on an improved cuckoo algorithm and variable step conductance increment method was proposed.</td>
<td>Further improvement of local convergence characteristics and enhancement of local convergence stability in the MPPT tracking algorithm for generating fuzzy logic control laws.</td>
<td>[21]</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Artificial neural network method</td>
<td>Using particle swarm optimization algorithm to track maximum values.</td>
<td>Quick and effective achievement of maximum power tracking control.</td>
<td>[22]</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Incremental conductance</td>
<td>Propose a concise control method for maximum power point tracking (MPPT) based on the incremental conductance method and the adaptive superposition of stepless voltage disturbances.</td>
<td></td>
<td>[23]</td>
</tr>
<tr>
<td>Photovoltaic array reconstruction</td>
<td>1</td>
<td>TSO, MSMA</td>
<td>Propose a hybrid optimization algorithm based on the tuna algorithm (TSO) and the improved slime mold foraging algorithm (MSMA).</td>
<td>The accuracy is higher than that of the individual TSO and MSMA algorithms, resulting in better tracking speed and accuracy.</td>
<td>[24]</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Adjusting the number of battery series and parallel connections</td>
<td>Seriously mismatched battery cells are connected in series.</td>
<td>Increase in the output power of the photovoltaic system and reduction of the impact of adaptation.</td>
<td>[25]</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Shadow detection hybrid method</td>
<td>An effective hybrid method for shadow detection has been proposed, which combines deep neural networks (DNN) and gradient boosting decision trees (GBDT) for joint operation.</td>
<td>Improvement of the energy production performance of photovoltaic arrays.</td>
<td>[26]</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Improving the mayfly algorithm</td>
<td>A reconstruction method based on the improved mayfly algorithm (IMA) was proposed.</td>
<td>Can effectively improve the output power of photovoltaic arrays and reduce mismatch losses.</td>
<td>[27]</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Minimum equilibrium difference method</td>
<td>A photovoltaic array reconstruction method based on the grid connected (TCT) structure has been proposed.</td>
<td>The output power of the reconstructed photovoltaic array has significantly increased.</td>
<td>[28]</td>
</tr>
</tbody>
</table>
Peak power estimation theory and genetic algorithm

A dynamic reconstruction method based on peak power estimation has been proposed. Improvement of the efficiency of photovoltaic array power optimization and reconstruction. Reduction of the mismatch between photovoltaic modules and increase in the output power of the photovoltaic system. Improvement of the power of the PV-TEG hybrid system reconstructed through SHO in all three arrays. [29]

Switch control method

Control the switch without changing the specific position of the photovoltaic module. [30,31]

System reconstruction based on the hippocampus optimizer

A PV-TEG hybrid system reconstruction method based on the sea horse optimizer (SHO) was proposed.

Differential power processing

1. Distributed algorithm
   Interaction between local voltage measurement and the differential power converter. Implementation of MPPT tracking of series photovoltaic submodules. Avoidance of losses caused by power mismatch in photovoltaic modules. [33]

2. Processing of resonant switched capacitor converters
   Handling differential power among series-connected photovoltaic modules. Realization of the optimal output of solar energy systems. [34]

3. The combination of membrane swarm algorithm and radial basis function neural network
   A hybrid method to improve the performance of photovoltaic systems and achieve optimal output of large system power for solar systems. [35]

4. Differential power processing topology
   The use of zero current switches has the ability to monitor local MPPT. Achievement of local MPPT tracking on a single photovoltaic component. [36]

5. A differential processing architecture system for SLC topology
   Designed a differential power processing (DPP) converter with a switched inductor capacitor (SLC) topology structure. Increase in the output power of photovoltaic systems. [37]

The integrated technology of solar photovoltaics, photovoltaics, and thermal energy can simultaneously generate both energy benefits. This technology improves the efficiency of the comprehensive utilization of solar energy, while also meeting the needs of users for high-quality electricity and low-quality thermal energy. This section will analyze the research background and current status of solar photovoltaic-photothermal technology from four aspects: system theory research, system structure, system cycle working fluid, and system component research, as shown in Table 3. Although most scholars use solar photovoltaic comprehensive utilization systems as the main method for experimental research, they can also analyze the performance of the system from a theoretical perspective by building models, writing programs, and boundary conditions.
Table 3. Theoretical study of PV/T system.

<table>
<thead>
<tr>
<th>Technology Application</th>
<th>Serial Number</th>
<th>Main Content</th>
<th>Main Conclusions</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modeling and programming</td>
<td>1</td>
<td>Managing various uncertainties, such as solar radiation, through adaptive risk avoidance stochastic programming methods.</td>
<td>The proposed method is very effective in coordinating multi-energy scheduling, minimizing operational costs/risks, and other aspects.</td>
<td>[38]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Studied the irreversibility of Al₂O₃ single-bond Cu/water hybrid nanofluid (NF) in PVT solar collectors.</td>
<td>Improvement of PV/T efficiency.</td>
<td>[39]</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Introduced theoretical and experimental research on finned one-way air type photovoltaic/thermal (PV/T) solar collectors.</td>
<td>The simulation and experimental results are in good agreement.</td>
<td>[40]</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Theoretical research was conducted on the solar greenhouse of PV/T system from the perspectives of energy and environment.</td>
<td>Optimized energy and energy efficiency.</td>
<td>[41]</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>A new equivalent circuit was established to estimate the output capacity of PV/T solar collectors.</td>
<td>This circuit can be used to evaluate the thermal and electrical energy generated by the system.</td>
<td>[42]</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Developed a program for calculating finite volume, which can accurately obtain the temperature-related performance of the system.</td>
<td>Obtained optimal design parameters with maximum efficiency.</td>
<td>[43]</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Developed and validated a computational model that can be used to evaluate the impact of main control parameters on PV/T collectors.</td>
<td>The calculation results and experimental verification are good.</td>
<td>[44]</td>
</tr>
<tr>
<td>Boundary conditions and changes in operating conditions</td>
<td>1</td>
<td>A numerical simulation study was conducted on the flow and heat transfer characteristics inside PV/T collectors with different cooling network structures.</td>
<td>Optimized the flow and heat transfer performance of the collector.</td>
<td>[45]</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>A new method based on 9E analysis was adopted to numerically evaluate the innovative heat dissipation method integrated into solar photovoltaic thermal (PV/T) air collectors.</td>
<td>The quantitative results indicate that the application efficiency of this system in PV/T air collectors is relatively high.</td>
<td>[46]</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Explored the influence of different backplane materials on the performance of PV/T systems.</td>
<td>The temperature of the PV/T collector with a TPT backplane is low, and the COP of the collector with a Cu backplane is the highest.</td>
<td>[47]</td>
</tr>
</tbody>
</table>

The research on the structural design of solar photovoltaic and thermal comprehensive utilization systems mainly includes several aspects, including focusing system design and improving system circulation and connection methods, as shown in Table 4. In terms of focusing system design, Lasich [48] et al. proposed a trough-type concentrating solar photovoltaic-photothermal integrated system which improves the focusing level by reflecting solar light twice onto the collector. The experimental results show that the photoelectric conversion efficiency and photothermal efficiency of the system can reach 18.4% and 13.4%, respectively. In terms of improving the circulation and connection mode of the system, scholars such as Dubey [49] have conducted research on the series-parallel connection mode of collectors. The experimental results show that series connection can improve the system’s heat collection performance.
The research on the performance of the circulating working fluid in the solar photovoltaic-photothermal comprehensive utilization system mainly focuses on the characteristics of the system’s refrigeration working fluid. Many scholars have achieved many results in related research, as shown in Table 5. With the continuous advancement of research on the comprehensive utilization system of solar photovoltaic-photothermal energy and the improvement of theoretical research, many scholars have found that improving the structure of system heat exchange components can also improve system performance, as shown in Table 6. Scholars such as Ji [50] have adopted an integrated photovoltaic/photothermal technology, which uses a wall-mounted solar photovoltaic-photothermal collector to improve the insulation performance of the building.

Table 4. Study on structure design of PV/T system.

<table>
<thead>
<tr>
<th>Technology Application Number</th>
<th>Main Content</th>
<th>Main Conclusions</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV/T spotlight system design aspect</td>
<td>Simulation and experimental research were conducted on the thermoelectric output performance of a Fresnel high-power spotlight PV/T system based on direct microchannel cooling.</td>
<td>Stable output performance of the experimental system.</td>
<td>[51]</td>
</tr>
<tr>
<td>2</td>
<td>An optimized calculation method for the curvature radius of cylindrical mirrors was proposed.</td>
<td>Within a small range of the focusing plane, the energy flow density is high, and the uniformity is good, making it suitable for arranging photovoltaic cell modules.</td>
<td>[52, 53]</td>
</tr>
<tr>
<td>3</td>
<td>A study on systems without reflectors was conducted.</td>
<td>Significant improvement in overall efficiency.</td>
<td>[54]</td>
</tr>
<tr>
<td>4</td>
<td>Proposed a new photovoltaic, photothermal, and integrated solar water supply system installed on the roof of buildings.</td>
<td>The system is more efficient when using thermal siphon fluid flow circulation and larger capacity storage tanks.</td>
<td>[55]</td>
</tr>
<tr>
<td>5</td>
<td>A new type of PV/T heat pump system was proposed that combines PV panels with the heat pump system.</td>
<td>The photoelectric conversion efficiency of the experimental system can reach up to 15.50%.</td>
<td>[56]</td>
</tr>
<tr>
<td>6</td>
<td>A new type of flat panel heat pipe solar PV/T system was designed.</td>
<td>The heat transfer performance of flat heat pipes is best when the channel filling rate is 65%.</td>
<td>[57]</td>
</tr>
<tr>
<td>7</td>
<td>A new type of PV loop heat pipe hot water system was proposed.</td>
<td>In winter, it has higher photoelectric efficiency and comprehensive efficiency.</td>
<td>[58]</td>
</tr>
<tr>
<td>8</td>
<td>A new type of heat pipe PV/T system was proposed.</td>
<td>The actual energy gain of the system is 29.09% higher than that of the single photovoltaic system.</td>
<td>[59]</td>
</tr>
</tbody>
</table>

Improve the circulation/connection mode of the system

<table>
<thead>
<tr>
<th>Serial Number</th>
<th>Main Content</th>
<th>Main Conclusions</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Using two different configurations of PV/T collectors in series.</td>
<td>At medium mass flow rate, for a large number of PV/T collectors connected in series, the results are basically the same in both cases.</td>
<td>[60]</td>
</tr>
<tr>
<td>2</td>
<td>Proposed a novel hybrid system that uses the cooling water of a spotlight PV/T system as the pre-hot water for the lithium bromide Kalina cycle.</td>
<td>Overall system efficiency improved by 22.00–27.00%.</td>
<td>[61]</td>
</tr>
<tr>
<td>3</td>
<td>Based on the natural circulation PV/T hot water system, two different connection methods, series and parallel, were compared.</td>
<td>The heat that can be increased by series connection.</td>
<td>[62]</td>
</tr>
</tbody>
</table>
4 Designed a direct expansion solar PV/T system using Freon R22 refrigerant as the medium. Improved photoelectric efficiency by 16.30%. [63]
5 Established heat transfer models for different connection modes. Obtained the optimal inclination angle combination. [64]

Table 5. Study on the performance of the circulating working medium in a PV/T system.

<table>
<thead>
<tr>
<th>Serial Number</th>
<th>Main Content</th>
<th>Main Conclusions</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Experiments and analysis were conducted on the heat generation characteristics of solar collectors for cogeneration.</td>
<td>When the conversion efficiency is between 10% and 13%, the collector efficiency is between 40% to 50% and 20% at 20 °C and 40 °C brine temperatures, respectively.</td>
<td>[65]</td>
</tr>
<tr>
<td>2</td>
<td>Proposed a method of combining a filter with propylene glycol.</td>
<td>Realized wavelength selective utilization of sunlight.</td>
<td>[66]</td>
</tr>
<tr>
<td>3</td>
<td>Proposed a new type of refrigerant for use in PV/T systems.</td>
<td>Significantly improved the output capacity of photocells.</td>
<td>[67]</td>
</tr>
<tr>
<td>4</td>
<td>Proposed a nanofluid and apply it to a condensing PV/T system as a cooling medium.</td>
<td>The performance of this system is higher than that of the water-cooled type.</td>
<td>[68]</td>
</tr>
</tbody>
</table>

Table 6. Study on the structure design of PV/T system components.

<table>
<thead>
<tr>
<th>Serial Number</th>
<th>Main Content</th>
<th>Main Conclusions</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Numerical and experimental were conducted on the heat transfer characteristics of vertical photovoltaic collectors.</td>
<td>The efficiency of the collector increases with the increase of air mass flow rate, which reduces the temperature of the system.</td>
<td>[69]</td>
</tr>
<tr>
<td>2</td>
<td>Designed a new type of finned air fluid photovoltaic collector.</td>
<td>Thermal efficiency and electrical efficiency reach 37.10% and 13.56%, respectively.</td>
<td>[70]</td>
</tr>
<tr>
<td>3</td>
<td>Proposed a parameter that can characterize the energy return of active PV/T systems—actual energy return rate.</td>
<td>Under high-temperature conditions, this collector can improve the total efficiency by nearly 10.00%.</td>
<td>[71]</td>
</tr>
<tr>
<td>4</td>
<td>Proposed a special process for combining photovoltaic silicon cells with copper tube flow channels.</td>
<td>The actual energy yield of the heat pipe PV/T system is 29.09% higher than that of the PV system.</td>
<td>[72]</td>
</tr>
<tr>
<td>5</td>
<td>Designed a new PV/T system that combines a metal backplate PV module with a flat box collector.</td>
<td>The photoelectric and photothermal efficiency can reach 14.00% and 45.00%, respectively.</td>
<td>[73]</td>
</tr>
<tr>
<td>6</td>
<td>Proposed a special process for combining photovoltaic silicon cells with copper tube flow channels.</td>
<td>The lower the power generation efficiency of the system, the lower the initial water temperature of the water tank, and the higher the thermal and electrical efficiency.</td>
<td>[75]</td>
</tr>
</tbody>
</table>

2.2. PV/T Coupled Electrolysis Cell for Hydrogen Production

The methods of photovoltaic-photothermal coupling electrolytic cells include: (1) utilizing concentrated solar energy technology to provide heat and generate electricity through thermal cycling; (2) utilizing photovoltaic technology to provide electricity and heat through electric heaters; (3) utilizing concentrated solar energy technology to provide heat and photovoltaic technology to provide electrical energy. The coupling method of solar cells with electrolytic cells can be divided into two categories: direct coupling and
indirect coupling. Among them, the direct connection of solar cells to electrolytic cells represents a direct coupling method, offering advantages such as a high hydrogen production rate and reduced initial investment cost. Compared to direct coupling, indirect coupling involves the addition of MPPT, a DC-DC converter, and a hydrogen storage device. Although the cost increases, it effectively solves the matching problem between solar cells and electrolytic cells.

By coupling renewable energy with electrolytic cells, it not only achieves the absorption and suppression of renewable energy but also achieves the goal of supplying energy to electrolytic cells [76]. Many scholars have improved efficiency by optimizing PV/T-coupled hydrogen production systems. Powell et al. [77] reviewed hybrid strategies combining CSP with coal, natural gas, biofuels, geothermal, photovoltaic (PV), and wind energy. An overview of the different configurations of CSP hybrids with these other energy sources is also provided. Lv et al. [78] constructed a sustainable power generation system that combines solar thermal steam generation, photovoltaic power generation, solid oxide electrolysis cell (SOEC) water electrolysis for hydrogen production, and solid oxide fuel cell (SOFC) power generation to solve the energy storage difficulties faced by both photovoltaic and solar thermal power generation. The system parameters and energy efficiency optimization balance calculations were carried out. The system's full-day power generation efficiency can reach 9.4%. Landman et al. [79] proposed achieving centralized hydrogen production by separating hydrogen and oxygen and generating hydrogen in independent cells with a conversion efficiency of 7.50% from solar energy to hydrogen. Senthilraja et al. [80,81] developed a solar-assisted water splitting system to investigate the performance of hydrogen production systems based on photovoltaic-thermal (PV/T) collectors. The research results indicate that the outlet temperature, output voltage, and output power of the collector increase with the increase in flow rate, while the temperature of the photovoltaic module decreases with the increase in flow rate. Chandrasekar et al. [82] conducted experimental tests on a novel photovoltaic hot air (PVTa) system with semi-long fins downstream of the air channel to test its hydrogen production performance. The results indicate that among the five PV-assisted hydrogen production technologies considered, the PV system with semi-long, wavy fins produces the maximum amount of hydrogen gas. At the same time, a comprehensive consideration is given to the economy and efficiency of renewable energy-coupled electrolysis cells. The study discusses the thermodynamic performance and economic analysis under different conditions and strategies. Habibolahzade et al. [83] coupled a trough collector, ORC, thermoelectric generator, and PEM electrolytic cell to generate electricity and hydrogen, and analyzed the system from both thermodynamic and economic perspectives. Lin et al. [84] compared the performance of two types of solar collectors coupled with solid oxide electrolytic cells. A technical and economic analysis of a solar-powered high-temperature electrolysis system for the production of hydrogen and synthesis was proposed, and different strategies for utilizing solar energy were considered. Yadav et al. [85] provided a framework for the thermodynamic and economic evaluation of high-temperature steam electrolysis (HTSE) solar hydrogen production. A system configuration scheme for a solar-powered steam electrolysis device was proposed, and thermodynamic and economic analyses were conducted on solid oxide electrolysis cells driven by concentrated solar energy (CSP) and photovoltaic (PV) power plants under different temperature and current density conditions.

3. PV/T-Coupled Electrolysis Cell for Hydrogen Production

PV/T comprehensive utilization technology is a combination of solar photovoltaic technology and solar thermal collection technology [86]. The PV/T system was first proposed by Kern et al. [87]. This system has outstanding advantages in solar energy utilization per unit irradiation area, photovoltaic module photovoltaic efficiency, and comprehensive efficiency utilization. It has become one of the research hotspots in the field of solar energy comprehensive utilization in recent years.
With the continuous in-depth research of domestic and foreign scholars on the methods and systems of using solar energy for hydrogen production, and the induction and summary of various types of solar hydrogen production methods, it is finally concluded that solar photovoltaic-photothermal coupled electrolysis cell hydrogen production has more prominent advantages compared to other forms of hydrogen production methods [88]. But there are many types of solar collectors, so choosing the most suitable solar collector is the most crucial step.

3.1. Photovoltaic (PV) Systems

Photovoltaic power generation systems can convert solar radiation energy into electrical energy [89]. The main components that constitute these systems include solar cell arrays, battery packs, etc. Photovoltaic power generation technology has the characteristics of a simple structure and noise-free operation, making it a clean, safe, and renewable energy technology [90]. With the vigorous development of photovoltaic projects, the photovoltaic industry is increasingly receiving attention from various levels of government and departments. Photovoltaic power generation systems can generally be divided into independent systems, grid connected systems, and hybrid systems.

3.1.1. Independent Photovoltaic Power Generation Systems

Meteorological conditions, loads, and other factors can affect the reliability of independent photovoltaic power generation systems, so it is necessary to add energy storage and management equipment. The independent photovoltaic power generation system is mainly composed of solar cells, batteries, controllers, and blocking diodes [91], as shown in Figure 1. Independent photovoltaic power generation systems can be further divided into two categories: DC photovoltaic power generation systems and AC photovoltaic power generation systems [92].

![Figure 1. Block diagram of an independent photovoltaic system.](image)

3.1.2. Grid-Connected Photovoltaic Systems

The grid-connected photovoltaic system is connected to the power grid, and its structure is shown in Figure 2. This system can be divided into two types: centralized and distributed [93]. Centralized electricity is directly fed into the grid and then transmitted to users on demand, the energy flow involved in this process being unidirectional. Distributed systems do not require the transmission of electrical energy to the power grid, but rather direct distribution to electrical loads, commonly used in small systems [94].
3.1.3. Hybrid Photovoltaic Systems

A hybrid photovoltaic power generation system combines renewable energy with other forms of power generation, generally adding wind power and other types of power generation on top of photovoltaic energy. Its structural diagram is shown in Figure 3. Wind turbines and solar photovoltaic modules can simultaneously supply power to AC loads and the power grid, adding energy replenishment to the system, ensuring stable operation of the energy supply system while improving energy utilization efficiency.

3.1.4. Photovoltaic Systems Coupled with Electrolytic Cell Power Supply

Among different solar hydrogen production systems, photovoltaic-coupled electrolytic cell systems are currently a research hotspot. According to the connection with the power grid, photovoltaic/electrolytic cell systems can be divided into three categories [95]: independent systems, grid auxiliary systems, and peak shaving systems. The independent system shown in Figures 4 and 5 is completely independent, and the electricity required for the electrolytic cell is provided by photovoltaic modules. Due to the fluctuation and intermittency of solar energy, the received power of the electrolytic cell is not constant, resulting in a mismatch between the IeV characteristics of the electrolytic cell and the maximum power point of the photovoltaic cell. Therefore, it is necessary to add a DC/DC regulator in the system to solve this issue [96,97].

The second type is the power grid auxiliary system, as shown in Figure 6. In this configuration, photovoltaic cells provide as much power as possible, and the remaining energy is provided by the grid. Therefore, it is usually necessary to set a constant power...
supply in the system to improve its performance. Due to the need for additional detection units in the system, the investment cost of the system has increased, and the system adaptability is not strong.

![Diagram](image)

**Figure 4.** Grid-independent system (with a DC/DC regulator).

![Diagram](image)

**Figure 5.** Grid-independent system (no DC/DC regulator).

![Diagram](image)

**Figure 6.** Grid-assisted system.

The third type is peak shaving systems, where the actual use of photovoltaic cells is to generate electricity for the power grid. When the power grid is unable to absorb all the energy generated by photovoltaic cells, the excess energy generated by the cells is transmitted to the electrolytic cell for energy supply. Therefore, additional regulator units are required in the system, resulting in high hydrogen production costs, and the system is usually only used when power demand is unstable. In recent years, many scholars have conducted extensive research on hydrogen production systems using photovoltaic-coupled electrolysis cells, as shown in Table 7.
Table 7. Research status on hydrogen production from photovoltaic system coupled with electrolytic cell.

<table>
<thead>
<tr>
<th>Serial Number</th>
<th>Main Content</th>
<th>Main Conclusions</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>This study proposes a new configuration for a photovoltaic (PV) hydrogen production system.</td>
<td>Maximizing system performance and reducing power output and load mismatch caused by renewable energy fluctuations.</td>
<td>[98–100]</td>
</tr>
<tr>
<td>2</td>
<td>Three different methods for calculating the optimal electrolytic cell are studied.</td>
<td>The IV estimation method has the best performance, while the PV current method has the best effect.</td>
<td>[101]</td>
</tr>
<tr>
<td>3</td>
<td>Improvements in calculation methods related to electrolytic cells are explored.</td>
<td>Efficiency reaches up to 99%.</td>
<td>[102]</td>
</tr>
<tr>
<td>4</td>
<td>A new system for coupled electrolytic cells is proposed.</td>
<td>The hydrogen gas generated is consumed in the engine to generate electricity, increasing efficiency from 14.90% to 15.70%.</td>
<td>[103]</td>
</tr>
<tr>
<td>5</td>
<td>An energy optimization model for multi-energy interactions in wind power, photovoltaic hydrogen production, and hydrogen fuel cell systems (HPHFCs) for thermal power plants has been proposed.</td>
<td>Numerical examples and simulation results have verified the correctness and effectiveness of the model.</td>
<td>[104]</td>
</tr>
<tr>
<td>6</td>
<td>The energy utilization of the hybrid photovoltaic/electrolyte/fuel cell system is analyzed, and the photovoltaic array is installed on the roof to provide electricity.</td>
<td>51 PV cells with a capacity of 75 W, plus a 3.3 KW electrolytic cell, and two 480 W PEM fuel cells can completely supply energy to a 90 m² greenhouse.</td>
<td>[105]</td>
</tr>
</tbody>
</table>

3.2. Photothermal (PT) Systems

3.2.1. Thermodynamic Cycle Power Generation

Currently, photovoltaic power generation technology and concentrated photothermal power generation (CSP) technology are the two main solar power generation technologies. Photothermal power generation has the advantages of high efficiency and low cost. According to the different forms of cycles, CPS can be divided into organic Rankine cycles, Brayton cycles, and Stirling cycles [106]. Among them, the organic Rankine cycle is the most widely used. Compared to solar high-temperature thermal power generation, the solar organic Rankine cycle power generation system has a relatively simple structure and has been widely used.

The solar organic Rankine cycle power generation system is mainly composed of components such as a collector, heat storage tank, and oil-water heat exchanger. The schematic diagram of a typical solar organic Rankine cycle system is shown in Figure 7, where the solar collector can absorb solar energy, and the oil-water heat exchange can transfer heat to high-temperature water and organic working fluids.
3.2.2. Photothermal Systems Coupled with Electrolytic Cell Heating

Research has shown that if the annual global radiation at a specific location exceeds 1300 kWh/m², it can be seen that solar thermal systems are more cost-effective than photovoltaic modules. Solar collectors are divided into mainstream collectors, such as flat plate collectors, Fresnel collectors, parabolic groove collectors; and dish collectors. As shown in Table 8, by coupling different solar systems with electrolytic cells, the optimization and efficiency improvement of different energy supply modes and collectors, as well as the current research status of solar coupled electrolytic cells, are summarized.

Table 8. Research status of hydrogen production in photothermal-coupled electrolytic cell.

<table>
<thead>
<tr>
<th>Serial Number</th>
<th>Main Content</th>
<th>Main Conclusions</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Thermodynamic research and analysis were conducted on a solar-powered thermal-driven hydrogen production system.</td>
<td>The discharge efficiency of the collector initially increases with the increase of the surface temperature of the collecting fluid, and decreases with further temperature increase after 36 °C.</td>
<td>[107]</td>
</tr>
<tr>
<td>2</td>
<td>A new photothermal system is proposed.</td>
<td>The increase in system power reduces the failure rate of the trans critical CO2 condenser to 50%. The system can generate 7135 KW of power and 0.05 kg/s of hydrogen. The energy efficiency and thermal efficiency of the hydrogen production system are 87% and 88%, respectively. The efficiency and thermal efficiency of the power generation system are 24.79% and 22.36%, respectively.</td>
<td>[108]</td>
</tr>
<tr>
<td>3</td>
<td>A new system is proposed, utilizing a solar tower system to produce thermal and electrical energy for a high-temperature electrolytic cell system.</td>
<td></td>
<td>[109]</td>
</tr>
<tr>
<td>4</td>
<td>A new system is proposed, using fluorinated molten salt as a heat storage system.</td>
<td>The efficiency of the solar hydrogen production system reaches 12.70%.</td>
<td>[84]</td>
</tr>
<tr>
<td>5</td>
<td>Different scenarios for different solar collectors are defined and compared in terms of energy and economy.</td>
<td>The scheme using a heliostat collector can achieve a maximum efficiency of 10.6%.</td>
<td>[84]</td>
</tr>
<tr>
<td>6</td>
<td>A new system is proposed, with the addition of a PCM storage system.</td>
<td>Reduction in the average cost of hydrogen by 34%.</td>
<td>[110]</td>
</tr>
</tbody>
</table>

4. Electrolytic Hydrogen Production Methods

In current research, the main hydrogen production methods include natural gas steam reforming, petroleum reforming, coal gasification, and water electrolysis. Water
Electrolysis hydrogen production is a hydrogen production method that does not use fossil fuels as raw materials and generates hydrogen gas through the electrolysis of water. This method is based on electrochemical principles. By adding an electrolyte to water and then applying electricity between the two electrodes, the water molecules are decomposed into hydrogen and oxygen [111]. Water electrolysis hydrogen production technology can be divided into alkaline water electrolysis (AWE) technology, proton exchange membrane electrolysis water (PEM) technology, high-temperature solid oxide electrolysis water (SOEC) technology, and solid polymer anion exchange membrane (AEM) electrolysis water technology [112]. Among these, AWE electrolysis water technology is the most mature. The commercialization of PEM electrolysis water technology has developed rapidly in recent years. However, SOEC and AEM water electrolysis technologies are still in the initial stage of research. In 2022, the cumulative installed capacity of global AWE tanks was at least 727 MW, accounting for 52% of the total installed capacity. The proportion of installed capacity in PEM electrolytic cells continues to increase, with a cumulative installed capacity of at least 366 MW in 2022, a year-on-year increase of nearly 200%. The cumulative installed capacity in 2023 is expected to be close to that of alkaline electrolytic cells, exceeding 1 GW [82].

Solar energy coupled electrolysis of water for hydrogen production can achieve sustainable hydrogen production and solar energy storage. Hydrogen and oxygen are generated by electrolysis of water in an electrolytic cell, and the reaction can be expressed as:

$$H_2O(l) + 237.2(KJ/mol)_{electricity} + 48.6(KJ/mol)_{heat} \rightarrow H_2 + 0.5O_2$$ (1)

Among the four different types of electrolysis, the operating conditions and media are all different. Table 9 summarizes and compares the characteristics of the four main electrolysis water hydrogen production technologies. The comparison of operating temperature and power consumption is shown in the form of bar charts in Figure 8a and Figure 8b, respectively.

**Table 9.** Comparison of technical characteristics of hydrogen production by electrolytic water [113,114].

<table>
<thead>
<tr>
<th>Serial Number</th>
<th>AWE</th>
<th>PEM</th>
<th>AEM</th>
<th>SOEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating temperature</td>
<td>70–90 °C</td>
<td>50–80 °C</td>
<td>40–60 °C</td>
<td>700–850 °C</td>
</tr>
<tr>
<td>working pressure</td>
<td>1–30 bar</td>
<td>&lt;70 bar</td>
<td>&lt;35 bar</td>
<td>1 bar</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>KOH 5–7 mol/L</td>
<td>PFSA</td>
<td>KOH or NaHCO₃</td>
<td>DVB polymer carrier doped with Yttria-stabilized Zirconia (YSZ)</td>
</tr>
<tr>
<td>Partitive membrane</td>
<td>PPS network fixed ZrO₂</td>
<td>Solid electrolyte</td>
<td>Solid electrolyte</td>
<td>Solid electrolyte</td>
</tr>
<tr>
<td>Electrode/catalyst (Oxygen side)</td>
<td>Nickel plated perforated stainless steel</td>
<td>Iridium oxide</td>
<td>High surface area Ni or NiFeCo alloy</td>
<td>Perovskite type</td>
</tr>
<tr>
<td>Current density (A/cm²)</td>
<td>&lt;0.8</td>
<td>1.0–4.0</td>
<td>1.0–2.0</td>
<td>0.2–0.4</td>
</tr>
<tr>
<td>Power consumption (KWh/Nm³)</td>
<td>4.2–5.5</td>
<td>4.3–6.0</td>
<td>4.5–5.5</td>
<td>3.0–4.0</td>
</tr>
<tr>
<td>Hydrogen purity</td>
<td>99.8%</td>
<td>99.9%</td>
<td>99.9%</td>
<td>99.9%</td>
</tr>
<tr>
<td>Electrode/Catalyst (Hydrogen side)</td>
<td>Nickel-plated perforated stainless steel</td>
<td>Platinum nanoparticles on black carbon</td>
<td>High surface area Ni</td>
<td>Ni/YSZ</td>
</tr>
<tr>
<td>Porous transport layer</td>
<td>Nickel contamination screen</td>
<td>Platinum-plated sintered porous titanium</td>
<td>Nickel foam</td>
<td>Nickel contamination Screen/Nickel foam</td>
</tr>
<tr>
<td>anode</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Porous transport layer</td>
<td>Nickel contamination screen</td>
<td>Sintered porous titanium /Carbon cloth</td>
<td>Nickel foam/Carbon cloth</td>
<td>/</td>
</tr>
<tr>
<td>cathode</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Bipolar plate anode | Nickel-plated steel | Platinum-plated titanium | Nickel-plated steel |
|------------------|------------------|-----------------------|------------------|
Bipolar plate cathode | Nickel-plated steel | Platinum-plated titanium | Nickel-plated steel |
Frame and scalability | PSU, PTFE, EPDM | PTFE, PSU, ETFE | PTFE, Si |
Maximum single cell size (Nm³/h) | 2000 | 500 | / |

Figure 8. Comparison of technical characteristics: (a) operating temperature of different types of hydrogen production technologies; (b) electricity consumption of different types of hydrogen production technologies.

4.1. Hydrogen Production from AWE

Although AWE technology has been widely applied, there is a problem of low hydrogen production efficiency. Usually, the working temperature of alkaline water electrolysis cells is about 70–80 °C, the working current density is about 0.25–0.4 A/cm², the gas pressure is 0.1–3.0 MPa, and the total efficiency is 62–82% [115,116]. The structural schematic diagram is shown in Figure 9a. There are two reasons for the low efficiency of AWE technology: firstly, the low electrolysis power, which is the main reason; secondly, impurities such as lye and water vapor in the gas production process need to be removed by adding auxiliary equipment, which not only increases the risk of gas leakage, but also reduces its hydrogen production efficiency.

Troostwijk [117] invented the AWE cell in 1789, and since then, it has been continuously promoted, becoming the most common and mature electrolysis technology. It has the lowest operating cost among various electrolytic cells. Unlike PEM electrolyzers, in alkaline batteries, water is fed into the cathode. After receiving electrons from external circuits, water splits into H₂ and OH⁻. The reaction between the anode and cathode is as follows:

\[
\text{Anode: } 4\text{OH}^- \rightarrow \text{O}_2 + 2\text{H}_2\text{O} + 4e^- \quad (2)
\]

\[
\text{Cathode: } 4\text{H}_2\text{O} + 4e^- \rightarrow 2\text{H}_2 + 4\text{OH}^- \quad (3)
\]
At present, the total installed capacity of alkali electrolysis devices in China is approximately 1500–2000 units, most of which are used for cooling hydrogen production in power plants. Figure 9 shows the typical system design and supporting facilities of an alkaline electrolytic cell. In recent years, through the continuous in-depth research of many scholars, the operating costs and initial investment costs of alkaline electrolytic cells [118] have been reduced, leading to an improved economy.

As shown in Figure 10, during the typical system operation of an AWE cell, the generated hydrogen and oxygen flow out of the cell with the circulating alkaline solution, forming a mixture of alkaline solution and gas on the hydrogen side and oxygen side,
respectively. Then it flows into the corresponding gas-liquid separator for cooling and separation. The separated oxygen is released, while a portion of the hydrogen is collected in the hydrogen storage tank and a portion enters the dryer for drying and reprocessing. The circulating alkaline solution enters the alkaline solution cooler for further cooling, then flows into the electrolytic cell, absorbs the heat of the electrolysis reaction, and the temperature rises. After being heated to its normal working temperature, it undergoes reaction recycling.

Figure 10. Typical system design and supporting facilities of AWE.

4.2. Hydrogen Production from PEM

The PEM water electrolysis hydrogen production technology has gradually become the mainstream technology for hydrogen production after nearly 60 years of development. The PEM water electrolysis cell is mainly composed of proton exchange membranes, anode and cathode catalytic layers, and other components. Figure 9b is a schematic diagram of the structure of a proton exchange membrane water electrolysis cell [119]. In the PEM electrolysis process, water is sent to the anode, where it is further decomposed into \( \text{O}_2^- \) and \( \text{H}^+ \). The resulting protons are then transferred through the membrane to the cathode, where they receive electrons and form \( \text{H}_2 \).

Due to the fact that oxygen and hydrogen are generated at different electrodes, there is no need for a separation device, which makes the system simpler compared to AWE cells for hydrogen production. The reaction between the anode and cathode is as follows:

\[
\text{Anode:} \quad 2\text{H}_2\text{O} \rightarrow \text{O}_2 + 4\text{H}^+ + 4e^- \quad (4)
\]

\[
\text{Cathode:} \quad 4\text{H}^+ + 4e^- \rightarrow 2\text{H}_2 \quad (5)
\]

PEM water electrolysis hydrogen production uses a perfluoro sulfonic acid proton exchange membrane instead of an asbestos membrane, which can effectively prevent electron transfer and improve the safety of the electrolysis cell. Due to the low hydrogen permeability of PEM, only water vapor needs to be removed, resulting in a higher purity of hydrogen production. This hydrogen production method has a wide range of pressure regulation and a strong ability to adapt to the volatility and indirectness of renewable energy. The PEM water electrolysis hydrogen production technology has a higher working current density, comprehensive efficiency, hydrogen volume fraction, and gas production pressure compared to alkaline water electrolysis hydrogen production technology, as well as a faster dynamic response.

The typical system design and supporting facilities of PEM electrolytic cells are shown in Figure 11. Due to limited hydrogen production, short lifespan, and high investment cost, PEM water electrolysis for hydrogen production is rarely applied in practical
engineering. At present, the bottleneck of PEM water electrolysis technology lies in the development and preparation of ultra-low load or ordered membrane electrodes.

Figure 11. Typical system design and supporting facilities of PEM electrolyzer.

4.3. Hydrogen Production from SOEC

High temperature solid oxide hydrolysis for hydrogen production (SOEC) is a highly promising water electrolysis technology among these four technologies. The electrolytic material of SOEC is solid oxide, with a working temperature of 800–1000 °C. Figure 9c is a schematic diagram of the structure of a solid oxide electrolytic cell. Compared to AWE water hydrogen production technology, the technical advantage of SOEC lies in its higher electrochemical performance and hydrogen production efficiency [120]. There are two methods to further improve its hydrogen production efficiency: on the one hand, the efficiency can be improved by increasing the contact area between the electrode and water vapor; on the other hand, the energy consumption required for the reaction can also be reduced by utilizing external high-temperature heat energy, thereby improving hydrogen production efficiency.

Solid oxide electrolytic cell (SOEC) is a new type of electrolytic cell proposed by Do-nitz and Erdle [121] in 1980. As shown in the figure, when a voltage is applied, the water vapor moves to the cathode electrolyte interface and is reduced to pure H2 and O2-. Then H2 diffuses back to the cathode and is collected on its surface as a hydrogen fuel, while O2- is conducted through a dense electrolyte. The electrolyte must have sufficient viscosity to effectively avoid the diffusion of steam and hydrogen, thereby preventing the recombination of H2 and O2-. At the electrolyte-anode interface, oxygen ions are oxidized to form pure oxygen and aggregate on the anode surface. The anode and cathode reactions are as follows:

\[
\text{Anode: } \quad \text{O}^{2-} \rightarrow 0.5\text{O}_2 + 2e^- \quad (6)
\]

\[
\text{Cathode: } \quad 2\text{H}_2\text{O} + 4e^- \rightarrow 2\text{H}_2 + 2\text{O}^{2-} \quad (7)
\]

Figure 12 shows a typical system design and supporting facilities diagram of a solid oxide electrolytic cell. The high temperature and humidity working environment requirements limit the selection of anode and cathode materials for electrolytic cells, and also restrict the large-scale promotion of SOEC hydrogen production technology.
4.4. Hydrogen Production from AEM

Solid polymer anion exchange membrane electrolysis technology is one of the most advanced water electrolysis technologies and also one of the preferred technologies for the large-scale application of green hydrogen in the future. However, only a few companies in the world are trying to commercialize it, and there are few application and demonstration projects. AEM technology combines the advantages of alkaline water electrolysis technology and PEM technology. Compared with alkaline water electrolysis technology, AEM technology has faster response speed and higher current density. Compared to PEM technology, AEM technology has lower manufacturing costs [122]. The structural diagram of the solid polymer anion exchange membrane water electrolysis tank is shown in Figure 9d. The working efficiency and equipment life of AEM electrolytic cells are mainly affected by the positive electrode materials, negative electrode materials, and anion exchange membranes.

As shown in Figure 9d, during equipment operation, raw water enters from the cathode side of the AEM equipment. Water molecules participate in the reduction reaction at the cathode and obtain electrons to form \( \text{OH}^- \) and \( \text{H}_2 \). After reaching the anode through a polymer anion exchange membrane, \( \text{OH}^- \) participates in the oxidation reaction, loses electrons, and forms \( \text{H}_2\text{O} \) and \( \text{O}_2 \). Improving the efficiency of AEM electrolysis equipment can be achieved by adding a certain amount of KOH solution or NaHCO₃ solution as an auxiliary electrolyte to the raw water.

AEM belongs to a branch of solid polymer electrolyte water electrolysis. The electrolyte is anion exchange membranes (AEMs), and the use of AEMs can effectively block the mixing of hydrogen and oxygen, improving the tolerance to pressure fluctuations on both sides of the membrane. Thus, renewable energy with strong volatility and intermittency can be directly used for electrolysis of water to produce hydrogen. The reaction between the anode and cathode can be written as:

\[
\text{Anode: } 4\text{OH}^- \rightarrow 2\text{H}_2\text{O} + \text{O}_2 + 4e^- \quad (8)
\]

\[
\text{Cathode: } 4\text{H}_2\text{O} + 4e^- \rightarrow 2\text{H}_2 + 4\text{OH}^- \quad (9)
\]

At present, there are very limited demonstration projects related to AEM technology, and most of them are still in the research stage. Figure 13 shows a typical system design and supporting facilities diagram for AEM electrolytic cells.
The working efficiency and service life of AEM electrolysis equipment are directly determined by the anion exchange membrane. Currently, anion exchange membranes are usually made of polymers as the main material. Due to the fact that AEM technology is still in the research and development stage, the most suitable material has not been found yet, so more research and development are still carried out using aromatic polymers.

5. Economic Analysis and Prospects

5.1. Economic Analysis

Economic analysis is an important aspect of hydrogen production projects. The cost of electrolytic hydrogen production consists of three components: the cost of the electrolytic cell, the price of renewable electricity, and other operating costs. The cost of general electrolytic cells accounts for about 20% to 25% of the cost of hydrogen production, where electricity accounts for the largest proportion, which is about 70% to 75%, and the operating cost is 5%. Therefore, to reduce the cost of electrolytic hydrogen production, the first step is to reduce the cost of electricity expenditure. Taking the more mature AWE technology and proton exchange membrane electrolysis technology as examples, Table 10 shows the cost comparison of two hydrogen production routes [123].

Table 10. Comparison of technical and economic indexes of AWE and PEM electrolysis.

<table>
<thead>
<tr>
<th>Item</th>
<th>AWE</th>
<th>PEM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Present</td>
<td>2030</td>
</tr>
<tr>
<td>Electricity price (CNY/kWh)</td>
<td>0.35</td>
<td>0.25</td>
</tr>
<tr>
<td>Unit power consumption (kWh/m³)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Unit power consumption cost</td>
<td>1.75</td>
<td>1.25</td>
</tr>
<tr>
<td>Hydrogen production capacity of equipment (Nm³/h)</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Power (KW)</td>
<td>5000</td>
<td>5000</td>
</tr>
<tr>
<td>Annual operating hours (h)</td>
<td>3000</td>
<td>3500</td>
</tr>
<tr>
<td>Equipment unit price (CNY/KW)</td>
<td>3500</td>
<td>2500</td>
</tr>
<tr>
<td>Equipment price (ten thousand CNY)</td>
<td>1750</td>
<td>1250</td>
</tr>
<tr>
<td>Period of depreciation (year)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Equipment depreciation (CNY/year)</td>
<td>875,000</td>
<td>625,000</td>
</tr>
<tr>
<td>Equipment operation and maintenance (CNY/year)</td>
<td>200,000</td>
<td>200,000</td>
</tr>
<tr>
<td>Unit water consumption (kg/m³)</td>
<td>0.82</td>
<td>0.82</td>
</tr>
<tr>
<td>Water price (CNY/kg)</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Hydrogen production cost (CNY/m³)</td>
<td>2.14</td>
<td>1.52</td>
</tr>
<tr>
<td>Hydrogen production cost (CNY/kg)</td>
<td>24.07</td>
<td>17.07</td>
</tr>
<tr>
<td>Proportion of electricity consumption cost (%)</td>
<td>82</td>
<td>82</td>
</tr>
</tbody>
</table>
5.2. Development Prospects and Prospects

In the case of small-scale conventional electricity, there is a significant cost difference between proton exchange membrane electrolyzers and alkaline electrolyzers. In large-scale production, the gap has narrowed, but the cost of proton exchange membrane electrolyzers has always been higher than that of alkaline electrolyzers. Although the scale effect restricts fixed investment, the higher price of catalysts in the PEM hydrogen production system leads to higher hydrogen production costs for the entire system, resulting in poor economic performance when the power output is stable. The advantages of PEM water electrolysis for hydrogen production lie in its fast response speed and ability to operate normally under extreme power conditions. Considering the significant changes in the output power of renewable energy and the long period of time between low and high load, the economy of hydrogen production by solar coupled PEM electrolysis cells can exceed that of solar coupled AWE cells in actual engineering projects.

The use of highly composite materials and the improvement of ion conductivity in film formation can further improve the performance of PEM water electrolysis hydrogen production technology and reduce costs [124]. Therefore, the technical bottleneck of the current PEM water electrolysis cell system lies in the preparation of proton exchange membranes that are inexpensive and chemically stable.

The solid oxide electrolysis technology for hydrogen production and the anion exchange membrane electrolysis technology for water are both in the experimental stage and have not yet achieved marketization. The current technical difficulties faced by the application of solid oxide water electrolysis technology for hydrogen production lie in the attenuation of the stack, the construction of the system, and the guarantee of system safety performance. Although the technological level of its reactors has made rapid progress, it still cannot meet the needs of practical applications. Therefore, further research on solid oxide water electrolysis hydrogen production technology is needed. At present, the research on alkaline solid polymer anion exchange membranes and the preparation of highly active nonprecious metal catalysts are still technical difficulties that need to be overcome in AEM water electrolysis hydrogen production technology.

6. Conclusions

The combination of solar energy systems and hydrogen production systems can improve energy efficiency while also playing an important role in the absorption and utilization of renewable energy. This article analyzes and summarizes the research results of key technologies for solar hydrogen production, and draws the following conclusions:

1. The solar photovoltaic system provides electricity for the hydrogen production system and generates heat through an electric heater to heat the electrolytic cell. The solar thermal system provides the required heat for the hydrogen production system. By using the MPPT algorithm and model optimization, the system efficiency can be improved by 16.30%, providing a reference route for the coupling of photovoltaic-photothermal systems with electrolytic cells.

2. Hydrogen production through water electrolysis can be divided into alkaline water electrolysis (AWE), proton exchange membrane water electrolysis (PEM), high-temperature solid oxide water electrolysis (SOEC), and solid polymer anion exchange membrane (AEM) water electrolysis. At present, the purity of hydrogen produced by the four-electrolysis water hydrogen production technologies is above 99.8%. Among them, AWE water electrolysis hydrogen production technology is the most mature of the four. The industrialization of PEM electrolysis water technology has developed rapidly in recent years. Both SOEC water electrolysis technology and AEM water electrolysis technology are in the initial stages of research.

3. From the installed capacity of the electrolytic cell, AWE is currently the mainstream hydrogen production method, and PEM has good development prospects. The cumulative installed capacity of global AWE tanks in 2022 was 727 MW, accounting for 52%
of the total installed capacity. However, the proportion of installed capacity in PEM electrolytic cells continues to increase, with a cumulative installed capacity of at least 366 MW in 2022, a year-on-year increase of nearly 200%. The cumulative installed capacity in 2023 is expected to be close to that of AWE, exceeding 1 GW.

(4) The cost of electrolytic cells accounts for approximately 20–25% of the cost of hydrogen production. The cost of PEM electrolytic cells is usually higher than that of other types of electrolytic cells, but in practical use, PEM has a fast response speed and can adapt to extreme power conditions. In the optimization of future PEM electrolytic cells, the overall performance and cost can be improved by optimizing the proton exchange membrane and ion conductivity. The hydrogen production costs of PEM and AWE electrolytic cells show a decreasing trend year by year. PEM predicts that the unit hydrogen production cost can be reduced by 19.37 CNY/kg by 2050, while AWE electrolytic cells show a decrease of only 10.49 CNY/kg. From this, it can be seen that PEM electrolytic cells have good development prospects.

(5) At present, the working temperature of the solid oxide electrolysis hydrogen production system is between 800 °C and 1000 °C, so the system faces issues such as stack attenuation, system construction, and system safety. The AEM electrolysis water technology is still in the research and development stage, currently facing the problem of the high cost of ion exchange membranes and catalysts within the system.

Author Contributions: Conceptualization, X.X. and Y.L.; methodology, Y.L.; software, Y.L.; validation, Y.L., B.R. and M.Z.; formal analysis, C.C.; investigation, D.B.; resources, A.J.; data curation, Y.L.; writing—original draft preparation, X.X. and D.B.; writing—review and editing, X.X.; visualization, X.X.; supervision, Y.L.; project administration, M.Z.; funding acquisition, M.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research, sponsored by the Science and Technology Department of Inner Mongolia Autonomous Region of China with project number 2020CG0066, focused on “Key technologies for solar energy application in ecological restoration and modern agriculture in deserts and saline-alkali lands”.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

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